

Water-Quality Analysis of an Intensively Used On-Farm Storage Reservoir in the Northeast Arkansas Delta

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Abstract The use of farm reservoirs for supplemental irrigation is gaining popularity in the Mississippi Alluvial Plain (MAP). Due to depletions of several aquifers, many counties within the MAP have been designated as critical-use groundwater areas. To help alleviate stress on these aquifers, many farmers are implementing storage reservoirs for economic and conservation benefits. When used in tandem with a tailwater recovery system, reservoirs have the potential to trap and transform potential contaminants (e.g., nutrients and pesticides) rather than releasing them through drainage into receiving systems such as lakes, rivers, and streams. Roberts Reservoir is an intensively used, 49-ha on-farm storage reservoir located in Poinsett County, Arkansas. Water-quality analyses and toxicity assessments of the reservoir and surrounding ditches indicated a stable water-quality environment with no observed toxicity present in collected samples. Results of this study suggest that water released into a local receiving stream poses no contaminant risk and could be maintained for irrigation purposes, thereby decreasing the need for additional groundwater depletion.

It is estimated that agriculture is responsible for consuming 70 % of the world's freshwater resources equating to a

total global water use of 7980 Gm³ year⁻¹ (Pimentel et al. 2004; Hoekstra and Chapagain 2007). Compared with the beginning of the 20th century, farmers are irrigating five times the amount of land to help feed a growing global population (O'Neill and Dobrowolski 2005). Pimentel et al. (2004) estimated that 65 % of United States agriculture's irrigation water comes from groundwater sources. In 2012, the state of Arkansas had 1,944,070 ha of irrigated land accounting for 9 % of the United States total irrigated hectares [United States Department of Agriculture (USDA) 2014a]. Arkansas used 6.78 trillion L of groundwater for irrigation in 2013 while using an additional 1.10 trillion L of on-farm surface water to supplement irrigation efforts (USDA 2014b). The eastern portion of Arkansas has a rich agricultural history as a primary producer for the state's most water intensive crop—rice. Poinsett County, Arkansas, harvested 43,178 ha of rice in 2012 accounting for 8 % of the state's rice crop, making it the top rice-producing county in the state (Hardke and Wilson 2013).

Groundwater in eastern Arkansas resides in two primary aquifers, the shallower Mississippi River Alluvial Aquifer and the deeper Sparta Aquifer. Overpumping throughout the years has resulted in the development of five different groundwater cones of depression, one of which is located in Poinsett County, Arkansas, and believed to be caused primarily by irrigation withdrawals. Mean annual groundwater decreases in Poinsett County, Arkansas, range between 0.15 and 0.3 m year⁻¹ (Schrader 2014). To continue sustainable agricultural production of rice and other crops in Poinsett County, eastern Arkansas, the United States, and—essentially—the entire world, alternative sources of irrigation must be developed and used. One suggested management practice is the combination of on-farm reservoirs and tailwater recovery (TWR) systems. This management practice is not widespread because of

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concerns about several factors including, but not limited to, construction costs, loss of productive acreage (for reservoir construction), water availability, crop rotation, and farm size (Popp et al. 2004). As with most management practices, there is no one singular, perfect solution. When used in conjunction with other management practices, such as laser leveling and short-season rice varieties, reservoirs and TWR systems may increase in profitability while simultaneously decreasing groundwater use (Popp et al. 2004).

Most historical limnological research on reservoirs has focused on large-scale systems used for hydroelectric energy production or flood control (Thornton 1990; Jones et al. 2008). Unfortunately, little limnological information exists on shallow depth reservoirs (<1 m) used specifically for crop irrigation. This research examined the water-quality characteristics of a 6-year-old, 49-ha irrigation reservoir in Poinsett County, Arkansas, used to irrigate 1200 ha of rice and soybeans (Fig. 1). The purpose of this research was to produce baseline monitoring information and water-quality characterization of a large, shallow irrigation reservoir used as a best-management practice (BMP) for soil and water conservation. The water quality of the reservoir was evaluated, and the sediment of the reservoir and its surrounding ditches was characterized.

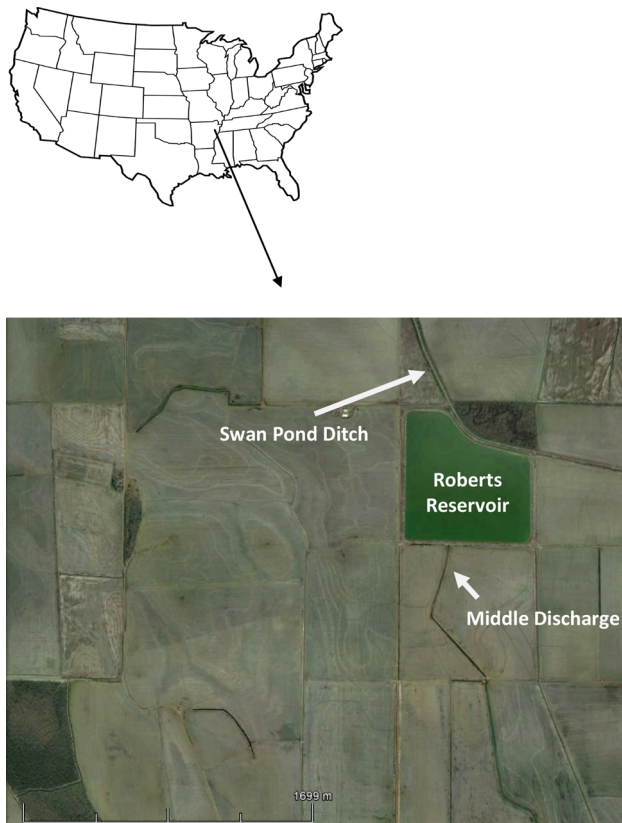


Fig. 1 Location of Roberts Reservoir and surrounding ditches, Poinsett County, Arkansas (USA)

Selected aspects of biological diversity within this system were identified as was monitoring the return water for a comparison of toxicity responses within different locations in the system.

Materials and Methods

Roberts Reservoir (Poinsett County, Arkansas, USA) is located approximately 10 km west of the city of Harrisburg, Arkansas, in the Mississippi Alluvial Plain (MAP) (Fig. 1). The 49-ha shallow reservoir had a mean water depth of 1 m. Two pumps located on the adjacent Swan Pond Ditch were used to fill the reservoir when necessary (Fig. 1). Reservoir water was drained by way of the middle discharge and then transported to various fields for irrigation.

Grab water samples were collected once a month during a 13-month period with appropriate seasonal representation among all sites. Specifically in the summer, both surface and bottom water samples were collected because the reservoir was being actively used for irrigation purposes. Samples were collected in 1-L Nalgene cubitainers and stored on ice until arrival at Arkansas State University (ASU) where they were immediately analyzed for constituents or used in toxicity assessments. At the same time, in situ water measurements—including temperature, conductivity, pH, total dissolved solids (TDS), and dissolved oxygen (DO)—were collected using a YSI-85 handheld multimeter and an Accumet pH meter. Orthophosphate, nitrate, and nitrite were measured in the laboratory using a HACHDR/890 colorimeter nutrient test kit with detection limits of 0.001, 0.01, and 0.005 mg L⁻¹, respectively.

Sediment was collected twice in July and once in June of the following year using a petite ponar. Samples (0.023 m²) were temporarily stored in 10-L containers on ice until arrival at ASU where they were transferred to a refrigerator (4 °C) until characterization and used in toxicity assessments. Reservoir and surrounding ditch sediments were characterized for cation exchange capacity (CEC), total solids, volatile solids, and particle size composition according to Gee and Bauder (1986).

Macroinvertebrates and fish from the reservoir and surrounding ditches were collected twice during the winter months and evaluated for density and diversity using a modified United States Environmental Protection Agency (USEPA) rapid bioassessment protocol technique partially described in Feldman et al. (2010). D-frame nets were used to collect organisms along the reservoir and ditch banks. Bottom-dwellers in the reservoir were sampled using a petite ponar (0.023 m²). Shannon diversity indices were calculated for the collection sites according to Brewer and McCann (1982).

Acute (48-h) assessments of toxicity using the fathead minnow (*Pimephales promelas*) and water flea (*Ceriodaphnia dubia*) were performed according to SEPA protocols (2002a). The ages of the test organisms were <14 days old and <24 h old for *P. promelas* and *C. dubia*, respectively. Assessments for *P. promelas* were performed from collected water samples (July and January) from the reservoir and ditches, whereas *C. dubia* assessments were performed on the same sites from water samples collected in July and August. In situ measurements of temperature, DO, and pH were performed throughout the experiment. The targeted end point during these short-term assessments was organism survival. Chronic (7 days) *P. promelas* and *C. dubia* assessments were also performed according to the USEPA (2002b) protocol on the same ditch and reservoir aqueous samples. Toxicity end points for these assessments were survival (both species), growth (*P. promelas*), and reproduction (*C. dubia*). Sediment-toxicity assessments (10 days) using *Chironomus tentans* were performed on samples collected from the reservoir and surrounding ditches in August and July of consecutive years. All assessments were performed according to USEPA protocol (2000) with toxicity end points of survival and growth.

Results and Discussion

Expected seasonal water-quality variations occurred within the reservoir (Table 1). Surface water nitrate concentrations increased between summer and fall samplings, which corresponds to results reported by Carruth et al. (2014) from TWR systems in the Mississippi Delta. Reservoir bottom grab samples in the summer months indicated a distinct difference in nitrate concentration between surface and bottom waters. This could potentially affect nutrient concentrations in outflow water because the reservoir outlet release is located near the bottom of the reservoir. By the

spring samplings, both nitrate and orthophosphate concentrations had decreased to < 1 mg L⁻¹. This is important because 30.5 % of the annual precipitation and 38.9 % of the annual surface runoff occurs during spring (March through May) (Pugh and Westerman 2014).

Little variation in water quality existed between either ditch (Swan Pond and Middle Discharge) or between the two ditches and the reservoir (Tables 2, 3). Analysis of variance results from seasonal water-quality data indicated no statistical difference between the three sites ($\alpha = 0.05$). Many researchers initially hypothesized that nutrients recycled through storage reservoirs and TWR systems could be reapplied onto fields through irrigation, thereby decreasing crop fertilizer inputs; however, this concept has yet to be substantially validated. In addition, crops such as rice receive and process nutrients in certain forms, not necessarily the dissolved form as evidenced by Moore et al. (2007). The temperature of the reservoir water versus groundwater for irrigation is, however, a practical benefit for rice crops. Warmer irrigation water pulled from a storage reservoir will decrease the cold shock on rice seedlings typically exposed to direct groundwater (14 °C) pumping. Abiotic stresses such as these cause world-wide decreases in average yields as much as 50 % (Mahajan and Tuteja 2005).

Basic sediment characterization of the reservoir and two surrounding ditches indicated similar results. Percent solids ranged from 48 ± 0 % (Swan Pond Ditch) to 67 ± 0 % (Middle Discharge). Volatile solids percentage in the reservoir (3 ± 0.3 %) was only slightly greater than at either Middle Discharge or Swan Pond Ditch (1 ± 0 % and 2 ± 0 %, respectively). Similarly, CEC was only slightly lower (8 ± 1) at the reservoir as opposed to either Swan Pond Ditch (10 ± 1) or Middle Discharge (12 ± 1). In all three locations, particle distribution was primarily silt, with the Middle Discharge sediment containing the most sand (17 ± 3 %). No measurable clay was detected in any of the

Table 1 Mean (± SD) seasonal water quality characteristics from Roberts Reservoir, Poinsett County, Arkansas, USA

Parameter	Summer (surface)	Summer (bottom)	Fall	Winter	Spring
pH	8.5 ± 0.3	8.1 ± 0.3	7.9 ± 0.3	8.3 ± 0.8	7.8 ± 0.6
Temperature (°C)	33.4 ± 7	32.4 ± 1	33.6 ± 1	10.4 ± 5	21.4 ± 6
Dissolved oxygen (mg L ⁻¹)	8.9 ± 0.8	6.4 ± 1.2	8.8 ± 0.9	12.2 ± 1.1	9.3 ± 1
Conductivity (us/cm)	330 ± 29	358 ± 8.6	360 ± 15	394 ± 47	386 ± 32
TDS (mg L ⁻¹)	167 ± 17	178 ± 5	179 ± 8	202 ± 17	192 ± 16
Nitrate (mg L ⁻¹)	0.9 ± 1	3.1 ± 0.6	3.6 ± 0.4	NA	0.6 ± 0.1
Nitrite (mg L ⁻¹)	0.04 ± 0.04	0.12 ± 0.01	0.11 ± 0.01	NA	0.01 ± 0.01
Phosphate (mg L ⁻¹)	0.22 ± 0.4	0.45 ± 0.31	0.38 ± 0.2	NA	0.04 ± 0.02

NA samples lost before analyses

Table 2 Mean (\pm SD) seasonal water quality characteristics from Swan Pond Ditch, Poinsett County, Arkansas, USA

Parameter	Summer	Fall ^a	Winter	Spring
pH	7.7 \pm 0.3	7.9	7 \pm 0.6	7.8 \pm 0.1
Temperature (°C)	30 \pm 5.8	32.9	10.8 \pm 5.3	21.8 \pm 6.9
Dissolved oxygen (mg L ⁻¹)	6.7 \pm 0.6	6.9	8.3 \pm 1.3	8.0 \pm 2.9
Conductivity (us/cm)	403 \pm 22	450	227 \pm 49	248 \pm 63
TDS (mg L ⁻¹)	202 \pm 10	226	116 \pm 22	124 \pm 31
Nitrate (mg L ⁻¹)	1.7 \pm 2	2.7	NA	0.8 ^a
Nitrite (mg L ⁻¹)	0.08 \pm 0.03	0.11	NA	0.08 ^a
Phosphate (mg L ⁻¹)	0.37 \pm 0.05	0.44	NA	0.26 ^a

^a Indicates only one set of collected samples

NA samples lost before analyses

Table 3 Mean (\pm SD) seasonal water-quality characteristics from Middle Discharge Ditch, Poinsett County, Arkansas, USA

Parameter	Summer	Fall ^a	Winter	Spring
pH	8.4 \pm 0.3	8.4	7.9 \pm 0.8	7.7 \pm 1.2
Temperature (°C)	32.1 \pm 7.3	35.2	12 \pm 5.4	23.4 \pm 10.1
Dissolved oxygen (mg L ⁻¹)	9.5 \pm 3.2	7.4	12.6 \pm 2	11.4 \pm 2.3
Conductivity (us/cm)	346 \pm 76	401	386 \pm 27	378 \pm 37
TDS (mg L ⁻¹)	173 \pm 38	200	193 \pm 13	189 \pm 19
Nitrate (mg L ⁻¹)	1.6 \pm 2	2.2	NA	0.5 ^a
Nitrite (mg L ⁻¹)	0.07 \pm 0.03	0.10	NA	0.03 ^a
Phosphate (mg L ⁻¹)	0.33 \pm 0.5	0.33	NA	BD

NA samples lost before analyses, BD lower than detection limit (<0.001 mg L⁻¹)^a Only one set of collected samples

samples. ANOVA results again indicated no significant differences ($\alpha = 0.05$) among sediment characteristics at any of the three collection sites. Although no clay was detected in the reservoir sediment sampling, the organic fraction of the silt component still provided binding sites for potential contaminants such as pesticides or phosphorus.

All acute (48-h) assessments for both *C. dubia* and *P. promelas* in water from the reservoir, Swan Pond Ditch, and the Middle Discharge resulted in no mortality (100 % survival). Chronic (7-day) assessments with *P. promelas* indicated no survival impacts (all sites yielded >80 % survival) or growth impairments (water from sites supported 0.3–0.4 mg growth/individual) compared with controls. Likewise, mean neonate production of *C. dubia* per individual ranged from 19 to 20. No reproduction impairment was noted compared with controls. Ten-day *C. tentans* assessments indicated no impacts of all sediment tested on either survival (>90 %) or growth (1.3–1.7 mg/individual) compared with controls.

Shannon diversity indices were relatively low for the reservoir, Swan Pond Ditch, and Middle Discharge Ditch (0.305, 0.686, and 0.363, respectively). Feldman et al. (2010) sampled benthic macroinvertebrates at 10 drainage ditch locations in the northeast Arkansas Delta region including a portion of Swan Pond Ditch. The mean annual

Shannon diversity index for larger ditches, such as Swan Pond Ditch, was $1.53 \pm 0.3.9$ (Feldman et al. 2010). This increase in diversity index may be due to a more intensive (multiple season) sampling regime. It is important to note that the absence of a diverse fauna in the reservoir (and others of similar size and function) does not necessarily imply toxic conditions. According to Wetzel (1990), most reservoirs (compared with lakes) have low biotic and benthic diversity. Within the reservoir, Chironomidae (18/m²), Oligochaeta (22/m²), and the decapod *Palaemonetes kadiakensis* (1/m²) were the only benthic macroinvertebrates collected. Callisto et al. (2005) reported low Shannon–Wiener index values in a reservoir along the São Francisco River in Brazil. Dominant groups sampled from that particular study included Mollusca, Oligochaeta, and Chironomidae (Callisto et al. 2005) much like those collected from the current study. No fish were collected within Roberts Reservoir because the only potential entry point into the reservoir is through relief pumps in Swan Pond Ditch. Although the current study was limited by funding, future fish assessments in Roberts Reservoir may benefit from electroshocking to obtain more accurate fish counts. The lack of diversity in the reservoir is most likely due to widely varying thermal conditions, noted in such shallow systems. Furey et al. (2006) also noted that different

drawdown regimes can affect benthic macroinvertebrates. Because the reservoir does not maintain a constant depth, especially during irrigation season, this could attribute to low macroinvertebrate diversity. In addition, homogenous habitat, as observed in the reservoir, has been reported to contribute to the absence of faunal diversity (Moyle and Mount 2007).

Slightly more diversity occurred in Swan Pond Ditch with Oligochaeta (22/m²), Chironomidae (22/m²), *Physella* (1/m²), *Gammarus* (1/m²), *P. kadiakensis* (48/m²), and Haliplidae (3/m²). Two fish species, *Lepomis* (10/m²) and *Gambusia affinis* (2/m²), were present in Swan Pond Ditch. Greater diversity in Swan Pond Ditch was expected because it receives multiple inputs from within the watershed and is approximately three times the size of the Middle Discharge. Diversity in the Middle Discharge was similarly diverse with Oligochaeta (1/m²), Chironomidae (2/m²), *Gammarus* (1/m²), *P. kadiakensis* (50/m²), *Podura aquatica* (4/m²), Corixidae (1/m²), and Haliplidae (1/m²). The only fish collected in Middle Ditch was *Lepomis* (2/m²).

With critical groundwater shortages in many intensive rice-producing areas, farmers are turning to irrigation reservoirs and TWR systems as soil and water BMPs. With no observed acute or chronic aqueous or sediment toxicity in the reservoir, potentially harmful effects of reservoir irrigation water are minimal. Water-quality concerns still exist when considering reuse of water whether it be from irrigation or other sources. Salinity and sodicity, in addition to ion, inorganic, and organic material concentrations, are all valid concerns for the use of degraded water (Pedersen et al. 2003; O'Connor et al. 2008). Examination should also be given to potential impacts of reused water on not only the crop receiving the irrigation but also any potential human health risks (e.g., pathogens, bacteria, metals, pesticides) from consuming such irrigated crops (Salgot et al. 2003; Toze 2006). At least preliminarily, farm-irrigation reservoirs displayed no observed aqueous or sediment toxicity, and nutrient concentrations in the surface water would not present a significant threat to downstream receiving systems in the event of a release. The only certainty with TWR and irrigation reservoirs is that much more evaluation and research is needed to fully understand their ecological, hydrological, and economic benefits.

References

- Brewer R, McCann MT (1982) Laboratory and field manual of ecology. Saunders, Philadelphia
- Callisto M, Goulart M, Barbosa FAR, Rocha O (2005) Biodiversity assessment of benthic macroinvertebrates along a reservoir cascade in the lower São Francisco River (Northeastern Brazil). *Braz J Biol* 65(2):229–240
- Carruth GW, Paz JO, Tagert ML, Guzman SM, Oldham JL (2014) Reusing irrigation water from tailwater recovery systems: Implications on field and stream-level nutrient status. ASABE paper no. 141913747. ASABE, St. Joseph, MI
- Feldman DL, Farris JL, Moore MT, Cooper CM (2010) A characterization of benthic macroinvertebrate communities in agricultural drainage ditches of the northeast Arkansas Delta, USA. In: Moore MT, Kröger R (eds) *Agricultural drainage ditches: Mitigation wetlands for the 21st century*. Research Signpost, Kerala, pp 17–35
- Furey PC, Nordin RN, Mazumber A (2006) Littoral benthic macroinvertebrates under contrasting drawdown in a reservoir and a natural lake. *J North Am Benthol Soc* 25(1):19–31
- Gee GW, Bauder JW (1986) Particle-size analysis. In: Black WC (ed) *Methods of soil analysis, part 1*. American Society of Agronomy, Madison, pp 398–406
- Hardke JT, Wilson CE Jr (2013) Trends in Arkansas rice production. In: Norman RJ, Moldenhauer KAK (eds) *B. R. Wells Rice Research Studies 2012*, Research Series 609, pp 38–47
- Hoekstra AY, Chapagain AK (2007) Water footprints of nations: water use by people as a function of their consumption pattern. *Water Resour Manag* 21:35–48
- Jones JR, Obrecht DV, Perkins BD, Knowlton MF, Thorpe AP, Watanabe S, Bacon RR (2008) Nutrients, seston, and transparency of Missouri reservoirs and oxbow lakes: an analysis of regional limnology. *Lake Reservoir Manage* 24:155–180
- Mahajan S, Tuteja N (2005) Cold, salinity and drought stresses: an overview. *Arch Biochem Biophys* 444:139–158
- Moore MT, Cooper CM, Kröger R (2007) Rice (*Oryza sativa*) as a remediation tool for nutrient runoff. *Bioremediat J* 11(4):165–170
- Moyle PB, Mount JF (2007) Homogenous rivers, homogenous faunas. *Proc Natl Acad Sci USA* 104(14):5711–5712
- O'Neill MP, Dobrowolski JP (2005) CSREES agricultural water security white paper. Washington, DC
- O'Connor GA, Elliott HA, Bastian RK (2008) Degraded water reuse: an overview. *J Environ Qual* 37:S157–S168
- Pedersen JA, Yeager MA, Suffet IH (2003) Xenobiotic organic compounds in runoff from fields irrigated with treated wastewater. *J Agric Food Chem* 51:1360–1372
- Pimentel D, Berger B, Filiberto D, Newton M, Wolfe B, Karabinakis E et al (2004) Water resources: agricultural and environmental issues. *Bioscience* 54(10):909–918
- Popp J, Wailes E, Young K, Smartt J (2004) Assessing the benefits of on-farm reservoirs and tail-water recovery systems. In: American Agricultural Economics Association Annual Meeting, Denver, CO
- Pugh AL, Westerman DA (2014) Mean annual, seasonal, and monthly precipitation and runoff in Arkansas, 1951–2011. USGS Scientific Investigations Report 2014-5006
- Salgot M, Vergés C, Angelakis AN (2003) Risk assessment in wastewater recycling and reuse. *Water Supply* 3(4):301–309
- Schrader TP (2014) Water levels and water quality in the Sparta-Memphis aquifer (middle Claiborne aquifer) in Arkansas, spring-summer 2011. USGS Scientific Investigations, Report, pp 2014–5044
- Thornton KW (1990) Perspectives on reservoir limnology. In: Thornton KW, Kimmel BL, Payne FE (eds) *Reservoir limnology: ecological perspectives*. Wiley, New York, pp 1–14
- Toze S (2006) Reuse of effluent water—Benefits and risks. *Agric Water Manag* 80:147–159
- United States Department of Agriculture (2014a) 2012 Census of agriculture United States summary and state data. www.agcensus.usda.gov/Publications/2012/Full_Report. Accessed 22 April 2015
- United States Department of Agriculture (2014b) 2012 census of agriculture farm and ranch irrigation survey (2013). Volume 3,

- special studies, part 1, AC-12-SS-1. www.agcensus.usda.gov/Publications/Irrigation_Survey/. Accessed 22 April 2015
- United States Environmental Protection Agency (2000) Methods for measuring the toxicity and bioaccumulation of sediment-associated contaminants with freshwater invertebrates (2nd edn). EPA/600/R-99-064. USEPA, Duluth, MN
- United States Environmental Protection Agency (2002a) Methods for measuring the acute toxicity of effluents and receiving waters to freshwater and marine organisms (5th edn). EPA 821-R-02-012. USEPA, Cincinnati, OH
- United States Environmental Protection Agency (2002b) Short-term methods for estimating the chronic toxicity of effluents and receiving waters to freshwater and marine organisms (4th edn). EPA-821-R-02-013. USEPA, Cincinnati, OH
- Wetzel RG (1990) Reservoir ecosystems: Conclusions and speculations. In: Thornton KW, Kimmel BL, Payne FE (eds) Reservoir limnology: Ecological perspectives. Wiley, New York, pp 227–238